# Simulation System Fidelity Assessment at the Vertical Motion Simulator


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## ABSTRACT

Quantifying simulation fidelity – the ability of a flight simulator to accurately recreate a flight environment – is a challenge that is incomplete. Assessing the cueing fidelity of a ground-based flight simulator requires a comparison with actual flight data. Two experiments conducted at the Vertical Motion Simulator (VMS) compared the handling qualities measured for a UH-60A Black Hawk simulation with those obtained from flight for the same tasks. Prior to the experiment, the simulator's motion and visual system frequency responses were measured and the aircraft math model was adjusted to incorporate the simulator motion system delays, ensuring that the overall helicopter response to control inputs closely matched those of the actual aircraft. The motion system gains and washouts were also adjusted to provide the most realistic motion cues for each evaluation task. The optimized motion system fidelity was then evaluated against the modified Sinacori simulation fidelity assessment criteria. In the first experiment, the handling qualities ratings (HQRs) in the VMS simulation for the Sidestep and Bob-up maneuvers were within one HQR of those given in the flight tests. The second experiment HQRs for the ADS-33 Slalom maneuver were nearly identical between flight and the simulation. The ADS-33 Vertical maneuver HQRs results were mixed, with one pilot rating the simulation equivalent, and the second pilot rating the simulation worse than flight. In addition to recording HQRs in the second experiment, a new Simulation Fidelity Rating (SFR) scale developed by the University of Liverpool and the National Research Council, Ottawa was evaluated for use on a research and development simulator. It is recommended that, when using SFR ratings for assessment of simulator fidelity, the pilot be given time to become acquainted to the simulator layout. Furthermore, the selected maneuvers should give the pilots the opportunity to adapt their techniques in order to obtain appropriate performance on their first simulation run.


## INTRODUCTION

Various methods to determine simulator fidelity have been proffered, and several scales have been developed to measure fidelity. Research and development (R&D) simulators like the Vertical Motion Simulator (VMS) at NASA Ames Research Center typically have been used to assess simulator fidelity by comparing handling qualities ratings (HQRs) between simulator and flight for a given task. White, et al. argued that matching HQRs is not sufficient to guarantee high fidelity [1] but believes a better way to measure fidelity is to compare piloting technique between the aircraft and simulator for a given task [2]. Regardless of how simulator fidelity is measured, achieving adequate fidelity can be challenging due to necessary compromises required for ground-based motion simulation includes reduced motion envelope, motion/visual system transport delays, visual cueing differences, and math model fidelity.


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Considerable research on cueing of ground based motion simulation has helped to better understand and mitigate the adverse effects of the simulation system on pilot performance. Knotts and Bailey advocated keeping the added delay from the simulator motion to less than 50 msec for a high gain task to limit the degradation of handling qualities ratings [3]. Mitchell, et al. showed that a motion transport of 80 msec degraded the handling qualities rating (HQR) from level 1 to level 2 [4]. Sinacori hypothesized [5], and Schroeder extended [6], a criterion for defining the quality of simulator motion based on the gain and phase of the motion software filters. Mitchell and Hart suggested minimizing the mismatch between motion and visual delays [7]. Gum and Martin suggested techniques for reducing math model delays [8]. These research studies addressed individual aspects of ground based flight simulation, but did not look at the response of the simulation system from control input to cue onset and compare it to actual flight data.

In 2012, two experiments on the VMS assessed the fidelity of a UH-60A Black Hawk helicopter simulation. The first experiment, named SimOpt [9], reproduced a Bob-up and Sidestep task from an experiment in 1989 [10] that consisted of back-to-back flight test and VMS simulation. The second experiment tested the new Simulation Fidelity Rating (SFR) scale developed by the University of Liverpool (UoL) and the National Research Council, Ottawa (NRCO) [2] originally developed to assess the fidelity of training simulators. A back-to-back VMS simulation and flight test using a UH-60A Black Hawk flying Slalom and Vertical maneuvers was used to test the SFR scale for use on an R&D simulator.

The results of these experiments demonstrated the improvement in simulation results when the end-to-end simulation system response is optimized to be similar to flight. This paper describes the SimOpt and SFR scale evaluation experiment (named SFRE), the simulation systems optimization, and compares simulation performance and pilot opinion with that of actual flight. The use of the SFR rating scale will also be discussed.

## VERTICAL MOTION SIMULATOR

### A. Description

The Vertical Motion Simulator, with its large motion envelope, provides the realistic cueing environment necessary for performing handling qualities studies. The VMS motion system, shown in Figure 1, is an uncoupled, six-degree-of-freedom motion simulator that moves within the confines of a hollow ten-story building. Schroeder, et al. concluded that larger simulator motion envelopes provide closer HQRs to flight than small motion envelopes for the same tasks [11]. Additionally, pilots gave large motion higher confidence factor ratings and achieved lower touchdown velocities compared to small motion simulators.

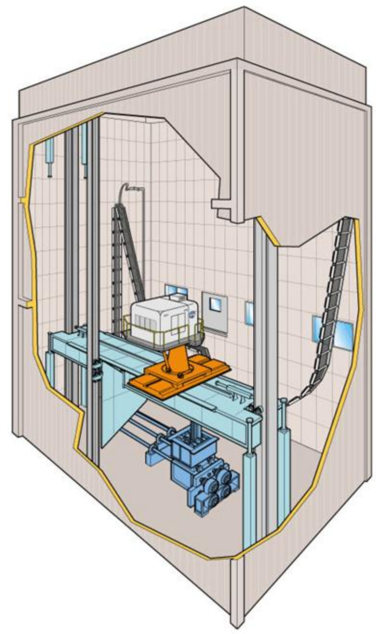


**Figure 1. Vertical Motion Simulator.**

The VMS motion capabilities are provided in Table 1. Included in the table are two sets of limits: system limits that represent the absolute maximum level attainable under controlled conditions; and operational limits that represent attainable levels for normal piloted operations [12].

The VMS has five interchangeable cabs (ICABs) with each having a different out-the-window (OTW) visual field-of-view (FOV) that is representative of a class of aircraft. The ICABs are customized for research by installing various flight controls, instruments, instrument panels, displays, and seats to meet specific research requirements.

A Rockwell-Collins EPX5000 computer image generator creates the OTW visual scene for up to seven window-collimated displays for the ICAB with the largest FOV. Standard flight instrumentation and other aircraft information, as needed for an experiment, are provided on head-down displays. The OTW and head-down display graphics are customized for each experiment.

**Table 1. VMS motion system performance limits (From Ref. 12).**

| Degree of Freedom | Displacement | | Velocity | | Acceleration | |
|---|---|---|---|---|---|---|
| | System Limits | Operational Limits | System Limits | Operational Limits | System Limits | Operational Limits |
| Longitudinal | ±4 ft | ±3 ft | ±5 ft/sec | ±4 ft/sec | ±16 ft/sec$^2$ | ±10 ft/sec$^2$ |
| Lateral | ±20 ft | ±15 ft | ±8 ft/sec | ±8 ft/sec | ±13 ft/sec$^2$ | ±13 ft/sec$^2$ |
| Vertical | ±30 ft | ±22 ft | ±16 ft/sec | ±15 ft/sec | ±22 ft/sec$^2$ | ±22 ft/sec$^2$ |
| Roll | ±0.31 ft | ±0.24 rad | ±0.9 rad/sec | ±0.7 rad/sec | ±4 rad/sec$^2$ | ±2 rad/sec$^2$ |
| Pitch | ±0.31 ft | ±0.24 rad | ±0.9 rad/sec | ±0.7 rad/sec | ±4 rad/sec$^2$ | ±2 rad/sec$^2$ |
| Yaw | ±0.42 ft | ±0.34 rad | ±0.9 rad/sec | ±0.8 rad/sec | ±4 rad/sec$^2$ | ±2 rad/sec$^2$ |

The high-fidelity flight controls are heavily modified and optimized McFadden hydraulic force-loader systems' with a custom digital-control interface. The custom digital-control interface allows for comprehensive adjustment of the controller's static and dynamic characteristics [13]. Force-loader characteristics may be varied during simulated flight as necessary for studying pilot cueing concepts using inceptors. A variety of aircraft manipulators, ranging from the regular column-and-wheel type to conventional rotorcraft controls and side sticks may be combined with the force-loader systems.

## B. Motion System

The cockpit motion cueing algorithms use high-pass (washout) filters and a rotational/translational cross-feed arrangement shown schematically in Figure 2. The computed pilot station accelerations of the modeled aircraft are second-order high-pass filtered, and attenuated, before commanding the motion drive system. Turn coordination and induced acceleration compensation account for the cross-coupled motion commands and provide the correct cues at the pilot's station. A low-pass filter tilts the simulator to provide steady-state longitudinal and lateral acceleration cueing at low frequency [14].

The VMS motion system may be adjusted for each simulation task by selecting the motion cueing filter gains and frequencies that provide the most realistic motion cueing within the simulator motion envelope. The motion tuning is a subjective process where the project pilot flies the maneuver and evaluates the motion cuing. A motion-tuning expert then adjusts the filter gains and washouts to satisfy the pilot while staying within the operational motion envelope.

The motion cueing dynamics, as defined by the selected gains and washout parameters, are then assessed against the

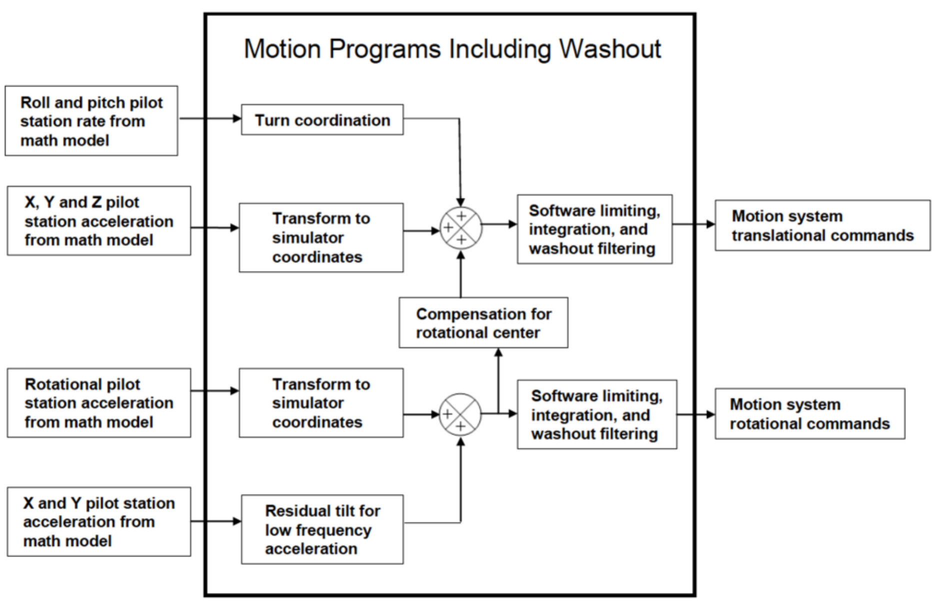



**Figure 2. VMS motion algorithm schematic.**

modified Sinacori criteria described by Schroeder [6]. The modified Sinacori criteria plots show the gain and phase distortion imposed by motion filters at 1 rad/sec. Figure 3 shows the modified Sinacori criteria plot for the Bob-up maneuver for each motion axis. Actual flight would display zero phase shift and unity gain and therefore would reside in the bottom right hand corner (see Fig. 3). Fixed-base simulators would have a motion gain and phase distortion of zero and would reside on the bottom left hand corner of the Sinacori plot.

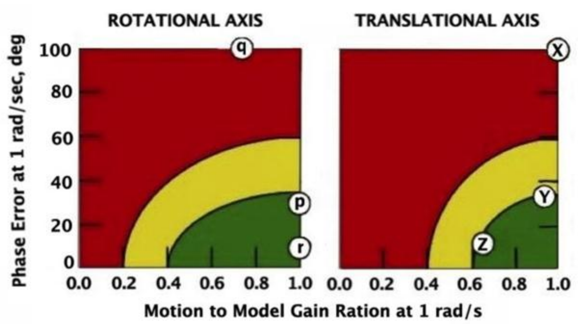



**Figure 3. Bob-up Maneuver Sinacori Plot.**

Schroeder and Grant recommended the following best practices [15] that were used to tune the motion system:

- Know your motion gains and washout frequencies in each axis; many simulator users do not know them and are therefore assuming unknown risks.
- Assess your motion cues with existing motion fidelity criteria; if you are in a low region, make sure you are satisfied that cues in that axis are not affecting your results adversely.
- If your motion cues are low fidelity for a particular task, then strongly consider changing the task to one that achieves the evaluation objectives but allows for higher motion fidelity.
- Overplot your math model angular rates and translational accelerations at the pilot's location with what your motion system is providing; make sure you are satisfied with any disparity.
- Try to find a task that allows the pilot to feel the vehicle's true control sensitivity.
- If your task has predominant frequencies, such as a dolphin maneuver over regular hills at a constant speed, adjusting the washout frequency is better than adjusting the gain to keep the motion cue in phase with the visual cue.

### C. Transport Delays

Transport delay is the time required for the simulator motion or visual system to react to an input from the pilot.

*1. Motion System Transport Delays*

Prior to this experiment, the frequency response of the VMS motion system was measured by independently driving each motion axis with twelve discrete sine waves specified by International Civil Aviation Organization (ICAO) Doc. 9625 [16], plus an additional frequency of 4.77 Hz. The amplitudes of the sine waves decreased with frequency to avoid exciting motion limits and structural modes. The resulting frequency response showed the system to behave as a pure time delay and exponential curve fits were computed using the least squares method to determine the equivalent time delay (see Table 2).

**Table 2. Motion system equivalent time delay.**

| Axis | Equivalent Time Delay [sec] |
|---|---|
| Pitch | 0.047 |
| Roll | 0.068 |
| Yaw | 0.048 |
| Longitudinal | 0.050 |
| Lateral | 0.069 |
| Vertical | 0.067 |
| Visual | 0.062 |

The frequency response of the motion system was also measured using frequency sweeps driven by a chirp signal, injected directly into the motion system over a frequency range of 0.2 – 20 rad/s over two minutes. CIFER [17] was then used to compute the frequency response plots and determine the equivalent time delay for the motion system. The results of the two different measurements agreed as shown in Appendix A.

*2. Visual System Transport Delay*

The visual system transport delay was measured by injecting chirp signals into the pitch axis at a frequency range of 0.2 – 30 rad/s over two minutes. A board with a black upper surface and white lower surface was positioned directly in front of the aircraft in the OTW view. As the aircraft nose pitched up and down from the chirp signal, the transition from black to white was measured using a photodiode against the OTW projection screen recorded by the Mark 2 Image Dynamic Measurement System (IDMS-2) developed at the VMS[18].

The IDMS-2 uses the composite and vertical sync signals from an NTSC (National Television System Committee) or RGB (Red Green Blue) video signal to determine the relative position of a transition from a dark region of video to a bright region. The vertical sync signal references the beginning of a frame of video and is used in the IDMS-2 to reset the counters and detector logic. By comparing the video brightness in each line with a threshold level set by the user, the IDMS-2 counts the number of composite sync pulses from the end of vertical sync to determine the relative position of the dark to bright transition in the video field [19]. The data collected by IDMS-2 were analyzed using CIFER and the time delay was measured as a constant 62 msec over the tested frequency range.

## OBJECTIVES AND APPROACH

### A. Experiment 1 – SimOpt

In 1989, an experiment was conducted to assess the current capability to simulate the UH-60A helicopter on the VMS. This was accomplished by performing back-to-back flight tests using a UH-60A Black Hawk helicopter and VMS simulations using the GenHel math model. Four pilots flew Bob-up, Sidestep, and Dash/Quickstop tasks at the NASA Ames flight-test facility at Crows Landing Naval Auxiliary Air Station and the VMS [10].

In the 2012 SimOpt experiment [9] the Bob-up and Sidestep tasks from the 1989 experiment were repeated on the VMS. Replicating the simulation cueing experiment from the 1989 experiments was not possible due to the improvements made to both visual and motion systems since those experiments. Several VMS subsystems, such as the visual image generator and sound system, have been upgraded and the dynamics of the motion-base has been improved since 1989.

The objective of the SimOpt experiment was to compare pilot-vehicle performance of the Bob-up and Sidestep maneuvers to that of the 1989 simulation and the accompanying flight test. A hover task was also conducted during the SimOpt experiment. It is not discussed in this paper, because no flight test data existed for this task.

### B. Experiment 2 – SFRE

In August 2012 a back-to-back flight test and simulation, using a UH-60A Black Hawk flying Slalom and Vertical maneuvers, was used to assess simulator fidelity by comparing pilot-vehicle performance in the simulator to that of the actual aircraft. The flight test and simulation were performed at NASA Ames Research Center. The two experienced Black Hawk pilots flew the maneuvers in the actual aircraft in the morning, and within an hour, flew the same maneuvers in the VMS.

In addition to collecting quantitative data, HQRs and Simulation Fidelity Ratings (SFR) were also collected (see Appendix B). The SFR scale developed by UoL and NRCO was tested for applicability to engineering simulators for evaluating simulator fidelity. The SFR scale assesses pilot opinion on performance and technique adaptation in simulation as compared to flight. The fidelity ratings range from one to ten, similar to the Cooper-Harper pilot rating with one being the best fidelity. The fidelity ratings are then grouped into fidelity levels. The fidelity levels range from one, which is characterized as "Fit for Purpose" to four, which is characterized as "Not Fit for Purpose." Since the SFR scale does not identify the source of deficiencies in fidelity, a questionnaire provided by UoL, was also administered (see Appendix C).

The SFR scale, like the Cooper-Harper scale, utilizes a decision tree that the pilot will navigate to obtain the final rating. The pilot must decide the level of performance and technique adaptation relative to the aircraft, working through the decision to obtain a fidelity rating and level.

## EXPERIMENTAL SETUP

### A. UH-60A GenHel Math Model

The GenHel math model configured for the UH-60A helicopter is a nonlinear representation of a single main rotor helicopter, accurate for full range of angles of attack, sideslip, and rotor inflow. It is a blade element model where total rotor forces and moments are calculated by summing the forces from blade elements on each blade, determined from aerodynamic, inertial, and gravitational components. Aerodynamic forces are computed from aerodynamic function tables developed from wind tunnel test data.

To compensate for the inherent motion system delay of the VMS, the GenHel math model was modified by removing delay in the model to provide a more accurate pilot input-to-motion cue representation of the UH-60A vehicle [9]. Using the math model outputs as the "truth set" representing the actual flight vehicle, two techniques to reduce the equivalent time delay of the GenHel math model were implemented and tested. The first concentrated on the primary servo (actuator) models, and the second focused on the blade-element model of the main rotor. The equivalent time delay "recovered" in the model for the two techniques is shown in Table 3.

**Table 3. Equivalent time delay recovered from model.**

| Axis | Actuator Modification (sec) | Actuator plus Rotor Modification (sec) |
|---|---|---|
| Pitch | 0.013 | 0.045 |
| Roll | 0.016 | 0.064 |
| Yaw | 0.014 | 0.005 |
| Vertical | 0.014 | 0.016 |

### B. Model Configurations

*1. Baseline GenHel*

The baseline configuration is the standard UH-60A GenHel model that was used in the 1989 experiment, Slalom and Vertical maneuvers. There were no modifications to remove excess time delay from the math model to compensate for motion system delay (see Table 4).

The Slalom maneuver used the Baseline GenHel configuration because the rotor modification affects the vehicle dynamics [9], which can be objectionable to the pilot in a multi-axis task. The Vertical maneuver also used the Baseline GenHel configuration to keep the aircraft consistent throughout the SFRE experiment.

*2. Actuator Modification*

The actuator modification configuration used during the Bob-up maneuver reduces the time delay in the actuators only. The modified rotor was not used in the Bob-up and Vertical maneuvers because there is no significant time delay recovery from the model in the vertical axis (see Table 3). Table 4 shows equivalent time delay of the simulation system after recovering delay from the model.

*3. Actuator plus Rotor Modification*

The modified configuration for the Sidestep maneuver utilized both the actuator and rotor modification to reduce the model delay (see Table 4).

### C. Simulator Cockpit

The Rotorcraft Cab (R-Cab) used for this experiment has three horizontal windows and a chin window (see Fig. 4). The field-of-view for R-Cab is similar to F-Cab that was used in the 1989 simulation except that R-Cab has a chin window. The cockpit controls and seat shaker were the same as the 1989 experiment including the cyclic and collective force-feel characteristics. The analog gauges from the 1989 simulation were replaced with head-down displays.

### D. Tasks and Performance Criteria for Experiment 1 – SimOpt

The Bob-up and Sidestep maneuver were configured and performed exactly as in the 1989 experiment as described in Ref. 8. The OTW visual targets were recreated to the same specifications as in the past two simulations (see OTW view of sidestep left hover target shown in Figs. 5 and 6).

**Figure 4. R-Cab cockpit.**

In the 1989 simulation the motion gains and washouts were the same for all configurations. In the SimOpt experiment, the gains and washouts were tuned for each task. The project pilot flew the tasks prior to the experiment and the motion system gains and washouts were selected and assessed against the modified Sinacori criteria. An example of the modified Sinacori criteria for all axes is shown in Figure 3 for the SimOpt experiment. The green region illustrates "like flight" fidelity, yellow region would be considered "different from flight," and the red region "objectionably different from flight." These boundaries were defined in Ref. 6. The gains and washouts for the three maneuvers are shown in Appendix D.

The pilots familiarized themselves with each maneuver over a 40-minute period, operating the vehicle under the same configurations as experienced in evaluation runs. Once they were sufficiently familiar with the task, they were asked to complete at least two practice runs before flying three evaluation runs and providing an HQR. Performance and HQR data were collected on all evaluation runs.

**Table 4. Equivalent Time Delay of Simulation System by Maneuver.**

| Axis | Slalom & Vertical Maneuver | Bob-up Maneuver | Sidestep Maneuver |
|---|---|---|---|
| | Baseline GenHel (sec) | Actuator Modification (sec) | Actuators plus Rotor Modification (sec) |
| Pitch | 0.047 | 0.034 | 0.002 |
| Roll | 0.068 | 0.052 | 0.004 |
| Yaw | 0.048 | 0.034 | 0.032 |
| Longitudinal | 0.050 | 0.050 | 0.050 |
| Lateral | 0.069 | 0.069 | 0.069 |
| Vertical | 0.067 | 0.053 | 0.062 |

*1. Bob-up Maneuver*

The Bob-up maneuver was performed starting from a stabilized hover 106 ft away from the lower hover board, as shown in Figure 5. The pilot signaled the start of the task, started a timer, and then rapidly ascended 40 ft to the upper hover board. The pilot then signaled that he was stable, which then stopped the timer. The Bob-up and stabilization was to be completed within 10 sec. After stabilization, the top position was held for 5 sec until a tone sounded. The pilot then rapidly bobbed down 40 ft to the lower hover board and signaled that he was stable within 10 sec. The hover position was held for 20 sec after stabilization.

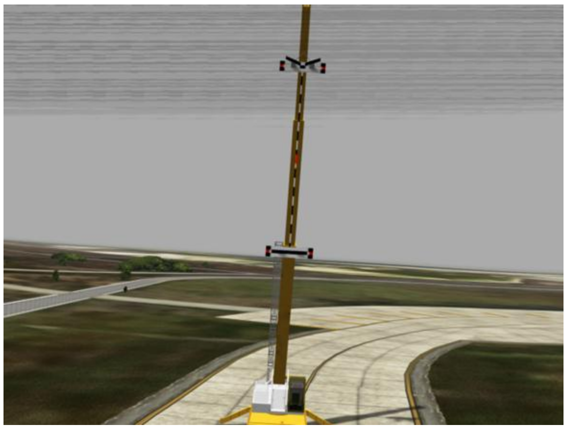


**Figure 5. OTW view of Bob-up lower hover. target.**

HQR Performance Standards:

Desired:

1. Complete translation and stabilization within 10 sec and with no objectionable oscillations.
2. Maintain altitude excursions within ±3 ft from hover board center after stabilization.
3. Heading excursions within ±5 deg of desired heading throughout maneuver.
4. Lateral excursions within hover board width after stabilization.

Adequate:

1. Maintain desired performance taking more than l0 sec to bob up (or down) and stabilize, or
2. Maintain desired performance for most of task except for occasional excursions that exceed, but are followed by return to, desired performance limits.

*2. Sidestep Maneuver*

The Sidestep maneuver was performed starting from a stabilized hover at the left or right hover board as shown in Figure 6. The pilot signaled the start of the maneuver, started a timer, and then rapidly translated 40 ft to the other hover board. The pilot then signaled that he was stabilized, which stopped the timer. The Sidestep translation and stabilization were to be completed within 7 sec. The stabilized hover was held for 20 sec. The maneuver was then repeated in the opposite direction.

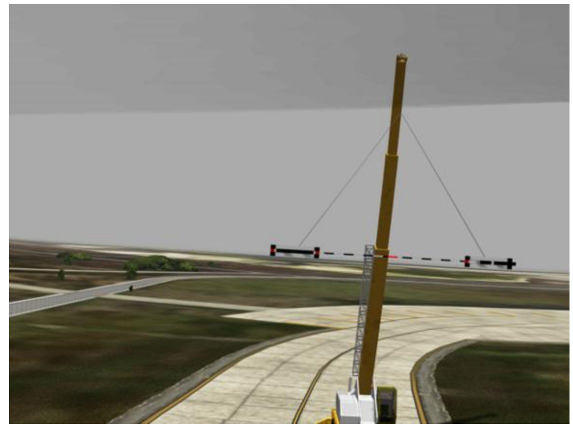


**Figure 6. OTW view of Sidestep left hover target.**

HQR Performance Standards:

Desired:

1. Complete translation and stabilization within 7 sec with no objectionable oscillations.
2. Maintain altitude excursions within ±3 ft from hover board centerline throughout the maneuver.
3. Maintain heading excursions within ±5 deg of desired heading throughout the maneuver.
4. Maintain lateral excursions (with reference to the pilot station) within hover board width after stabilization is reached.

Adequate:

1. Maintain the desired performance taking more than 7 sec to translate to right (or left) and then stabilizing, or
2. Maintain desired performance for most of task except for occasional stable excursions, which exceed, but are followed by a return to, desired performance limits.

### E. Tasks and Performance Criteria for Experiment 2 – SFRE

The two participating pilots flew the Vertical and Slalom maneuvers in an EH-60L Black Hawk helicopter. Pilot 1 was in the left seat and Pilot 2 in the right, and the two pilots took turns flying each task. Each task was flown a minimum of two practice runs before the pilot started the three data runs. After the three data runs the pilot was asked to give an HQR rating.

After completing the maneuvers in the actual aircraft, the pilots performed the same maneuvers on the VMS Black Hawk simulation. First, each pilot, without any practice runs, was asked to fly each task and give an SFR and

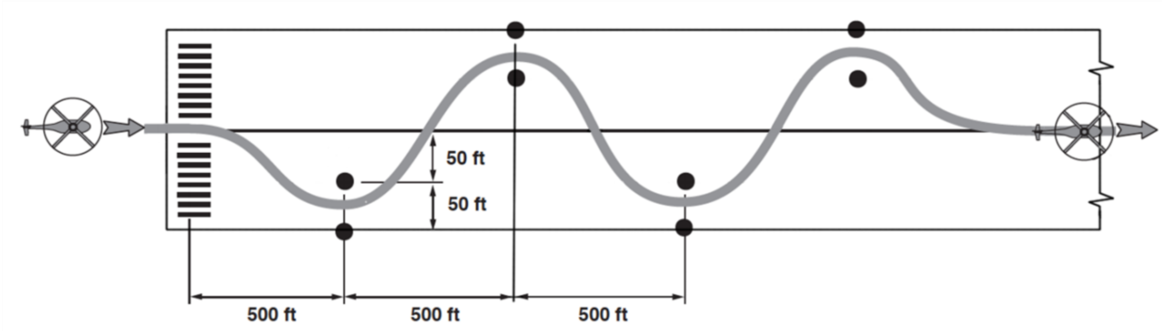



**Figure 8. Slalom maneuver diagram.**

complete a questionnaire. The developers of the SFR scale recommended that an SFR be recorded after the first simulation run, as they was believed that a pilot's greatest sensitivity to variations in simulator deficiencies will be upon the first exposure to a specific model/vehicle[20]. Each pilot then completed a minimum of three more runs before giving an HQR and another SFR.

The Vertical and Slalom maneuvers were based on those described in the ADS-33 Handling Qualities Requirements for Military Rotorcraft [21]. There were some minor changes to the ADS-33 course setup in the simulation due to R-Cab FOV limitations. In the Vertical maneuver, the

**Figure 7. OTW view of Vertical Maneuver.**

longitudinal position hover reference was relocated from 90 degrees clockwise of primary hover boards to 45 degrees clockwise of primary hover boards (see Fig. 7). In the Slalom maneuver, the cones were vertically elongated to fourteen times their normal height to make them more visible.

*1. Vertical Maneuver*

The Vertical maneuver was performed starting from a stabilized hover at an altitude of 38 ft. The pilot initiated a vertical ascent of 30 ft to the upper hover board position, stabilized for 2 seconds, then descended back to the initial hover position (see Fig. 7).

HQR Performance Standards:

Desired:

1. Complete translations and stabilization within 13 sec and with no objectionable oscillations.
2. Maintain altitude excursions within ± 3 ft from each hover board center
3. Heading excursions within ± 5 deg of desired heading throughout maneuver.
4. Lateral excursions within hover board width after stabilization.

Adequate:

1. Maintain desired performance taking more than l8 sec to complete entire transition and stabilize
2. Maintain lateral and longitudinal positions within ± 6 ft.
3. Maintain start and finish altitude within ± 6 ft.
4. Maintain heading within ± 10 deg.

*2. Slalom Maneuver*

The Slalom maneuver was performed starting in level unaccelerated flight and aligned with the centerline of the test course. The pilot then performed a series of smooth turns at 500-ft intervals (see Fig. 8). The maneuver was accomplished below the reference altitude and completed on the centerline, in coordinated straight flight.

HQR Performance Standards:

Desired:

1. Maintain airspeed of at least 60 knots throughout the course.
2. Accomplish maneuver below reference altitude of 100 ft.

Adequate:

1. Maintain airspeed of at least 40 knots throughout the course.
2. Accomplish maneuver below reference altitude of 100 ft.

## F. Pilots – SimOpt

Four Test Pilots with extensive rotorcraft experience ranging from 1850 to 4000 hours evaluated the SimOpt configurations.

1. Pilot 1 had 1850 hours of total rotorcraft flight time with 1500 hours of UH-60 time. Pilot 1 is currently an active Army UH-60 pilot.
2. Pilot 2 had 2350 hours of total rotorcraft flight time with 60 hours of UH-60 time. Pilot 2 is currently an active Army OH-58 pilot.
3. Pilot 3 had 3500 hours of rotorcraft time including 200 hour in tiltrotors but with no UH-60 hours. Pilot 3 has not had significant rotorcraft time in 6 years.
4. Pilot 4 had 4000 hours of rotorcraft time with 800 UH-60 hours. Pilot 4 is currently active in rotorcraft.

### G. Pilots – SFRE

Two Test Pilots with extensive rotorcraft experience ranging from 1850 to 2200 hours evaluated the SFR configurations.

1. Pilot 1 had 1850 hours of total rotorcraft flight time with 1500 hours of UH-60 time. Pilot 1 is currently an active Army UH-60 pilot.
2. Pilot 2 had 2200 hours of total rotorcraft flight time with 2000 hours of UH-60 time. Pilot 2 is currently active in rotorcraft research.

## RESULTS

### A. Experiment 1 – SimOpt

Figures 9 and 10 show the HQRs for the flight test and the two simulation experiments. The HQRs maximum, average, and minimum values are shown for each category denoted by the vertical bar showing the range of the minimum and maximum value with the solid square representing the average. Additional details and results on the SimOpt experiment, including pilot comments, can be found in Ref. 9.

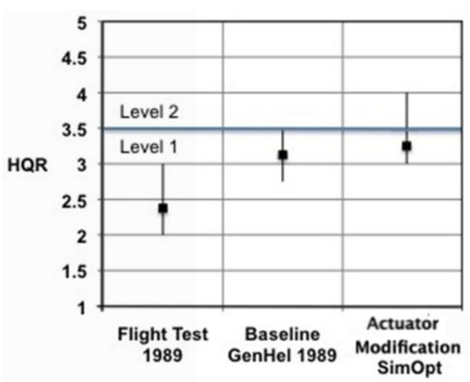



**Figure 9. Bob-up Maneuver HQRs.**

*1. Bob-up Maneuver*

It is difficult to compare flight HQRs with simulation HQRs unless the maneuvers are evaluated back-to-back with the same pilots. The 1989 simulation average HQRs was closest to flight, which had the HQRs taken immediately after the flight test (see Fig. 9).

In the SimOpt experiment, each maneuver was tuned specifically for the task while the motion system performance has been improved since the 1989 experiment. As a result, the average flight test HQR is less than one rating point better than the SimOpt configuration and the pilots on average were able to achieve level 1 handling qualities for the SimOpt configuration. The HQRs from the baseline and delay compensation configurations in the SimOpt experiment are similar to the 1989 simulation, though different pilots participated and there was no concurrent flight test.

*2. Sidestep Maneuver*

The average HQR for the modified Actuator plus Rotor Modification configuration is similar to those from 1989 (see Fig. 10). The average HQR from the flight test is less than one point better than the Actuator plus Rotor configuration. The SimOpt simulation system optimization did not improve the HQRs compared to the previous simulations.

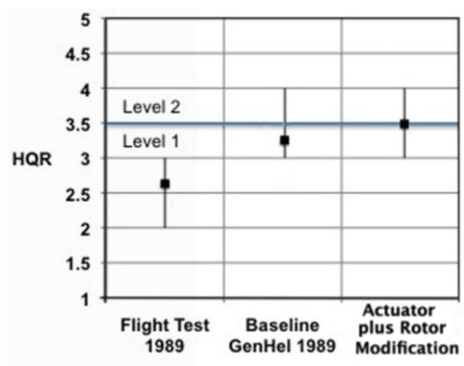



**Figure 10. Sidestep Maneuver HQRs.**

### B. Experiment 2 – SFRE

The two pilots provided HQRs for the test flight and simulation for the Slalom and Vertical maneuver after a minimum of three runs for each task (see Figs. 12 and 14). SFRs were given after the first run in the simulator and after becoming proficient for both the Slalom and Vertical maneuver (see Figs. 13 and 17).

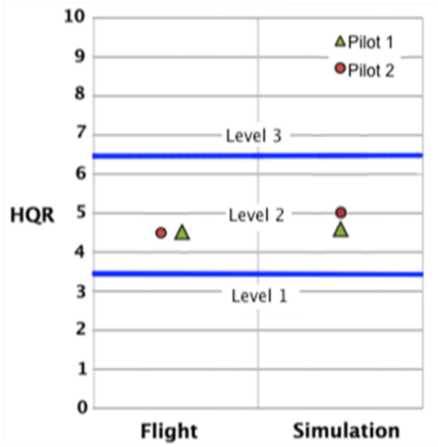



**Figure 11. Slalom Maneuver HQRs.**

*1. Slalom Maneuver*

Figure 11 shows the HQR assigned by each pilot for the Slalom maneuver for the flight test and the simulation. The HQRs for both pilots were nearly identical between flight and simulation. Figure 12 shows the SFR rating assigned by each pilot on the first run in the simulator and after task proficiency. The SFRs for both pilots were in Fidelity Level 2 range of the SFR scale, which is characterized as “Fidelity Warrants Improvement” (see Appendix B). The pilots’ SFR ratings were unchanged between the first run and when proficient. That infers that their performance and level of adaptation was unchanged when compared to flight. The difference between the two SFR ratings indicates that the perceived level of adaptation required was different between the two pilots.

Figure 13 plots the lateral position, ground speed and altitude as a function of longitudinal position of the aircraft from flight, the first simulation run and after task proficiency in the simulator for Pilot 1. Both pilots had similar performance on this task so representative runs were chosen to illustrate the performance trends.

During the flight tests, the pilots were able to maintain a more constant ground speed and altitude when compared with the simulator. The aircraft path also tended to peak in the lateral direction at the cones during flight, but before the cones, once the pilots were proficient in the simulator. The pilots commented that they felt they could not perform the task at as fast a ground speed in the VMS as in flight, which may explain this technique adaptation. The pilots also flew the aircraft at a lower altitude when proficient in the simulator because they could see the elongated cones better. Based on these differences in technique the SFR Fidelity Level Two rating, which is characterized as “Fidelity Warrants Improvement” is probably fitting even though the HQR’s for the same task is almost identical.

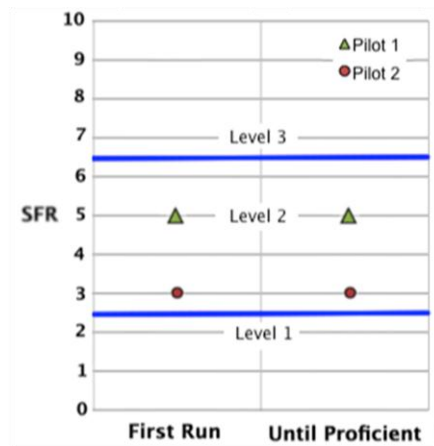



**Figure 12. Slalom Maneuver SFRs.**

The SFR scale states that if “Fidelity Warrants Improvement” then there is limited transfer of training for the selected task (see Appendix B) but it is unclear if this is true for the Slalom manuever. The technique used in the simulator may have also worked in actual flight with

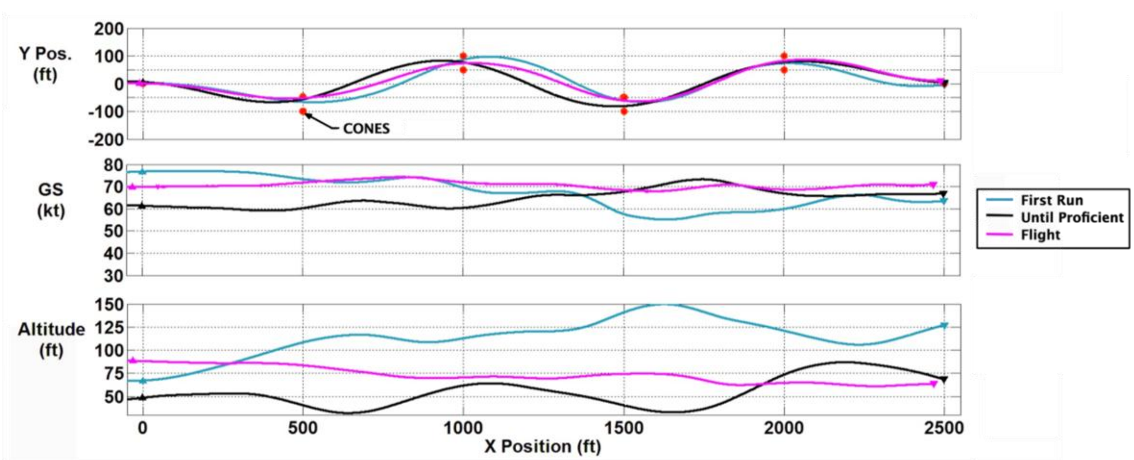



**Figure 13. Slalom Position, Ground Speed and Altitude for Pilot 1.**

equivalent performance.

The first simulation run had the largest variation in altitude and ground speed yet Pilot 1 gave the same SFR as when proficient, which infers the level of performance and adaptation were the same but the type of adaptation was probably different.

*2. Vertical Maneuver*

Figure 14 shows the HQR assigned by each pilot for the Vertical maneuver for the test flight and the simulation. The HQR for Pilot 1 was identical between flight and simulation. The HQR ratings for Pilot 2 were significantly worse in the simulator than in flight.

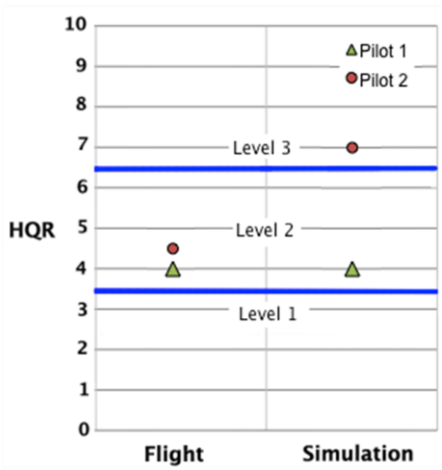



**Figure 14. Vertical Maneuver HQRs.**

Figure 15 shows the SFR rating assigned by each pilot on the first run in the simulator and after task proficiency. The SFR for Pilot 2 was in fidelity level three, which is characterized as "Not Fit for Purpose" on the SFR scale, for the first run and when proficient. The SFR fidelity rating did improve with proficiency but not enough to obtain a level two fidelity. Pilot 1 rated the first run as fidelity level two but improved the SFR rating to fidelity level one, which is characterized as "Fit for Purpose," after becoming proficient.

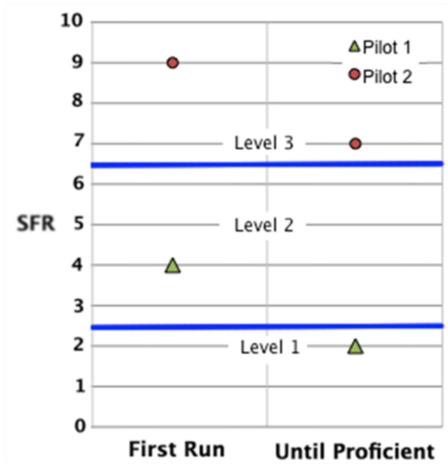



**Figure 15. Vertical Maneuver SFRs.**

Figure 16 shows the lateral and longitudinal position throughout the Vertical maneuver for Pilot 1. Pilot 1 was able to maintain ground position with minimal deviations throughout the task in flight and simulation. Pilot 1 commented that it was more difficult to judge longitudinal drift in the simulator. The reason was the location of the longitudinal hover board reference in the simulation. The longitudinal hover board reference had to be located 45 degrees from the vertical hover board due to FOV constraints in the simulator (see Fig. 7) instead of 90 degree as in the flight test.

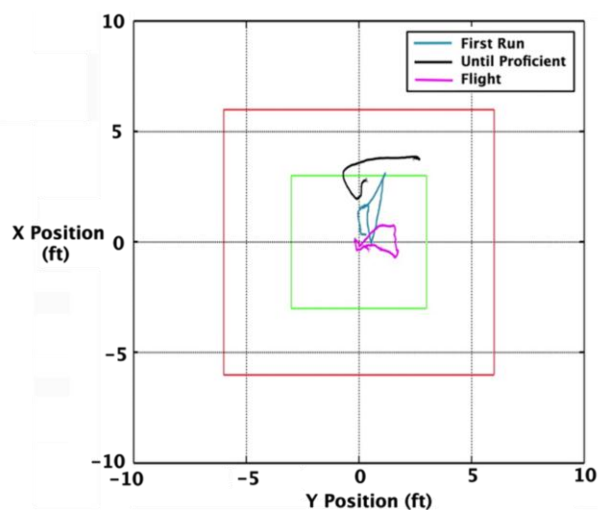



**Figure 16. Vertical Maneuver Position for Pilot 1.**

Figure 17 shows the aircraft altitude as a function of time for Pilot 1. Pilot 1 was less aggressive and took longer to transit between the hover boards on the first run when compared to flight and when proficient in the simulator. Figure 18 shows the collective position as a function of time for Pilot 1. The collective position for flight and once the pilot was proficient in the simulator are similar.

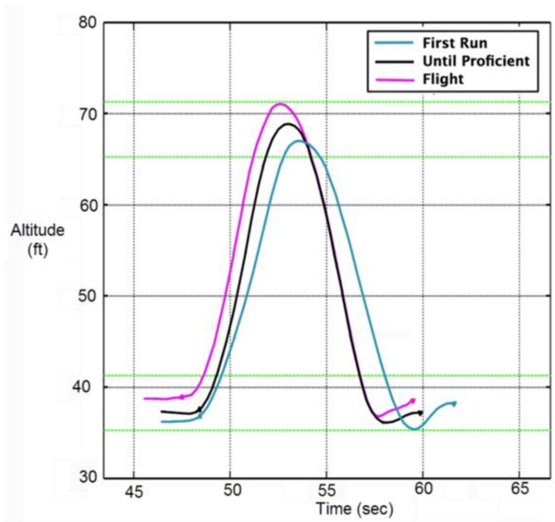



**Figure 17. Vertical Maneuver Altitude for Pilot 1.**

Figure 19 shows the lateral and longitudinal position throughout the Vertical maneuver for Pilot 2. The ground traces were different between flight, the first run in the simulator and when proficient in the simulator. Pilot 2 tended to drift laterally in flight but had trouble maintaining longitudinal position on the first run in the simulator. Pilot 2 was able to maintain a steady ground position once proficient in the simulator. Pilot 2's performance in flight and once proficient in the simulator were similar to Pilot 1's though his SFRs and HQRs were worse than Pilot 1's.

Figure 20 shows the aircraft altitude as function of time for Pilot 2. Pilot 2 was less aggressive and took longer to transit from the lower hover board to the upper hover board on the first run in the simulator as compared to flight, and when proficient in the simulator. Once at the top hover board, Pilot 2 took much longer to stabilize on the first simulation run as compared to flight and when proficient in the simulator.

Figure 21 shows the collective position as a function of time for Pilot 2. Pilot 2 was less aggressive in the first simulation run compared to flight as shown by the first collective pull at approximately 52 sec. Pilot 2's collective inputs, when proficient in the simulator, appear to be similar to flight and Pilot 1's collective inputs (see Fig. 18).

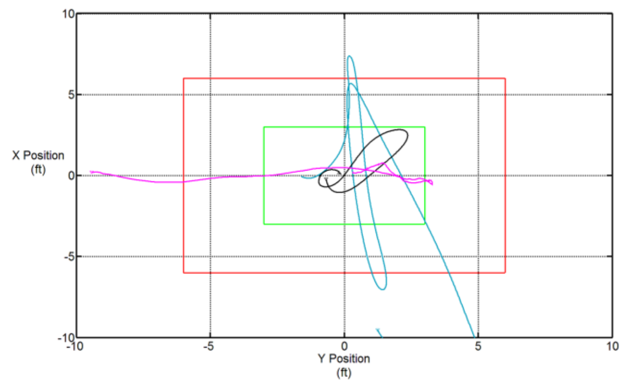



**Figure 19. Vertical Maneuver Position for Pilot 2.**

There are several possible explanations for the difference in HQR and SFR ratings between Pilot 1 and Pilot 2. These are: (1) Pilot 2 had little experience in the VMS and was not familiar with the generic cockpit layout as compared to Pilot 1 who has extensive VMS experience; (2) Pilot 2 flew the actual aircraft from the left seat and was informed of his positional drift from Pilot 1 in the right seat, but in the simulation Pilot 2 was in the right seat and was required to determine his own longitudinal position, which probably increased the workload compared to flight; (3) Pilot 2 may have needed more training runs in the actual aircraft; (4) Pilot 2's difficulty in stabilizing drift in the first simulation run seems to have left a lasting impression which did not change with his improved performance after he became

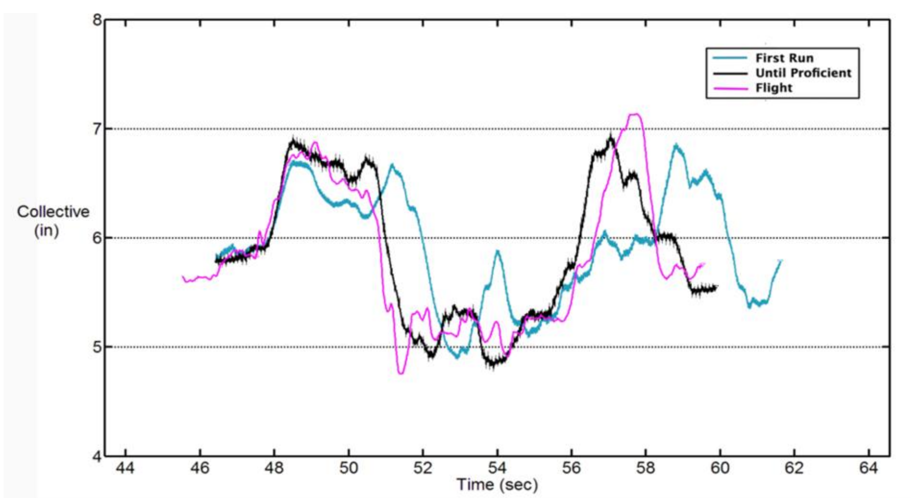



**Figure 18. Vertical Maneuver Collective Position for Pilot 1.**

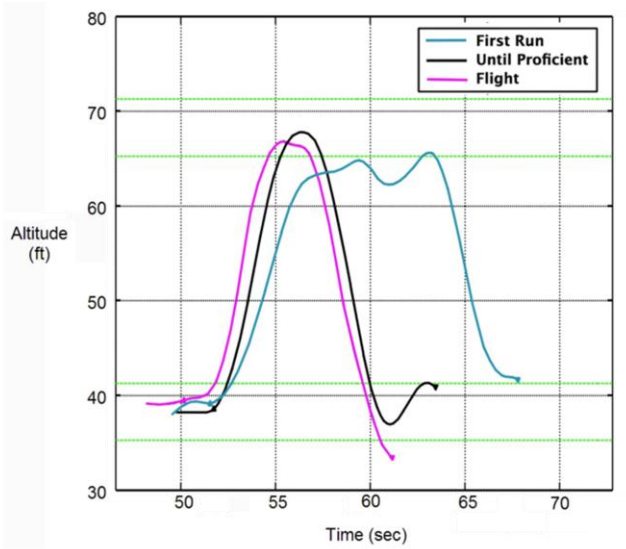



**Figure 20. Vertical Maneuver Altitude for Pilot 2.**

proficient in the simulation.

The length and repetitiveness of the task can also affect the SFRs. The pilots had time to adapt their technique within the repetitive Slalom task to obtain the required performance on the first run because of the length of the task. The Vertical task lasted approximately 10 to 15 seconds and was not repetitive. So there is no opportunity for a pilot to adapt a new technique on the first run in the simulator. This could skew the SFR rating, because the first box in the SFR flow chart (see Appendix B) asks if "fidelity permits task execution" and that might not be possible without time to modify their technique. It is important to give the pilots an opportunity to modify their technique so they can gauge the amount of adaptation necessary to execute the task to the best of their ability. To allow for this, maneuvers should be designed with enough repetition to allow the pilot time to adapt their technique within the task to obtain appropriate performance. Pilots should also be given the opportunity to get acquainted with the simulator, especially an R&D simulator, when the cockpit layout is not the same as the actual aircraft being simulated. In the actual aircraft, pilots have to fly to the test course, which serves as familiarization time, so it may be appropriate to have the pilot do the same in the simulator.

## SUMMARY AND CONCLUSIONS

Two experiments on the NASA Ames Vertical Motion Simulator (VMS) assessed simulator fidelity. The first experiment, named the SimOpt experiment, shows how to optimize the simulation system to maximize the simulation fidelity. The first step in the optimization process was characterizing the motion and visual system and determining the transport delays. The second step was to modify the GenHel math model configured for a UH-60A Black Hawk helicopter to remove excess delay to compensate for the time delay inherent in the motion system. Lastly, the motion systems gains and washouts were tuned specifically for each task and evaluated against the modified Sinacori simulation fidelity assessment criteria.

The results of the SimOpt experiment show that the VMS, optimized for Sidestep and Bob-up maneuvers, produce handling qualities ratings (HQRs) within one HQR from actual flight tests. These results were consistent across experiments conducted more than 20 years apart.

The second experiment, named Simulation Fidelity Rating Experiment (SFRE), was a back-to-back flight and VMS simulation experiment using a UH-60L Black Hawk helicopter and GenHel math model. Similar to the SimOpt experiment, the motion system gains and washouts were tuned specifically for each task and evaluated against the

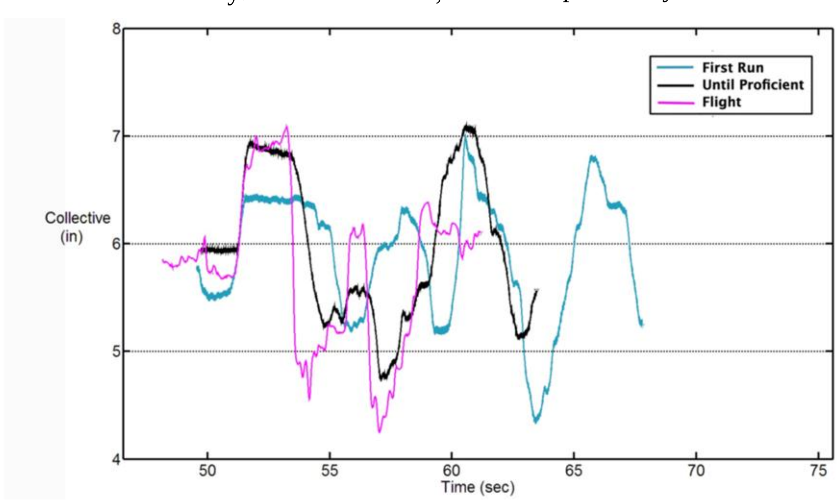



**Figure 21. Vertical Maneuver Collective Position for Pilot 2.**

modified Sinacori simulation assessment criteria. The HQRs for the ADS-33 Slalom maneuver were nearly identical between flight and the simulation for the two participating pilots. The ADS-33 Vertical maneuver HQRs were mixed, with one pilot rating the flight and simulation the same while the second pilot rated the simulation worse.

In addition to HQRs, Simulation Fidelity Ratings (SFR) was collected. The SFR scale was developed to assess the fidelity of training simulators. SFRs were collected at the VMS to test the use of the SFR scale on a research and development simulator.

Both pilots rated the Slalom maneuver in the simulator “Fidelity Warrants Improvement” after the first simulator run, and when proficient. The first pilot rated the Vertical maneuver “Fidelity Warrants Improvement” after the first simulation run and “Fit for Purpose” when proficient. The second pilot rated the Vertical maneuver “Not Fit for Purpose” after the first simulation run and when proficient. Although data was collected for only two pilots, the SFR appeared to be sound, addressing the measures of simulation fidelity.

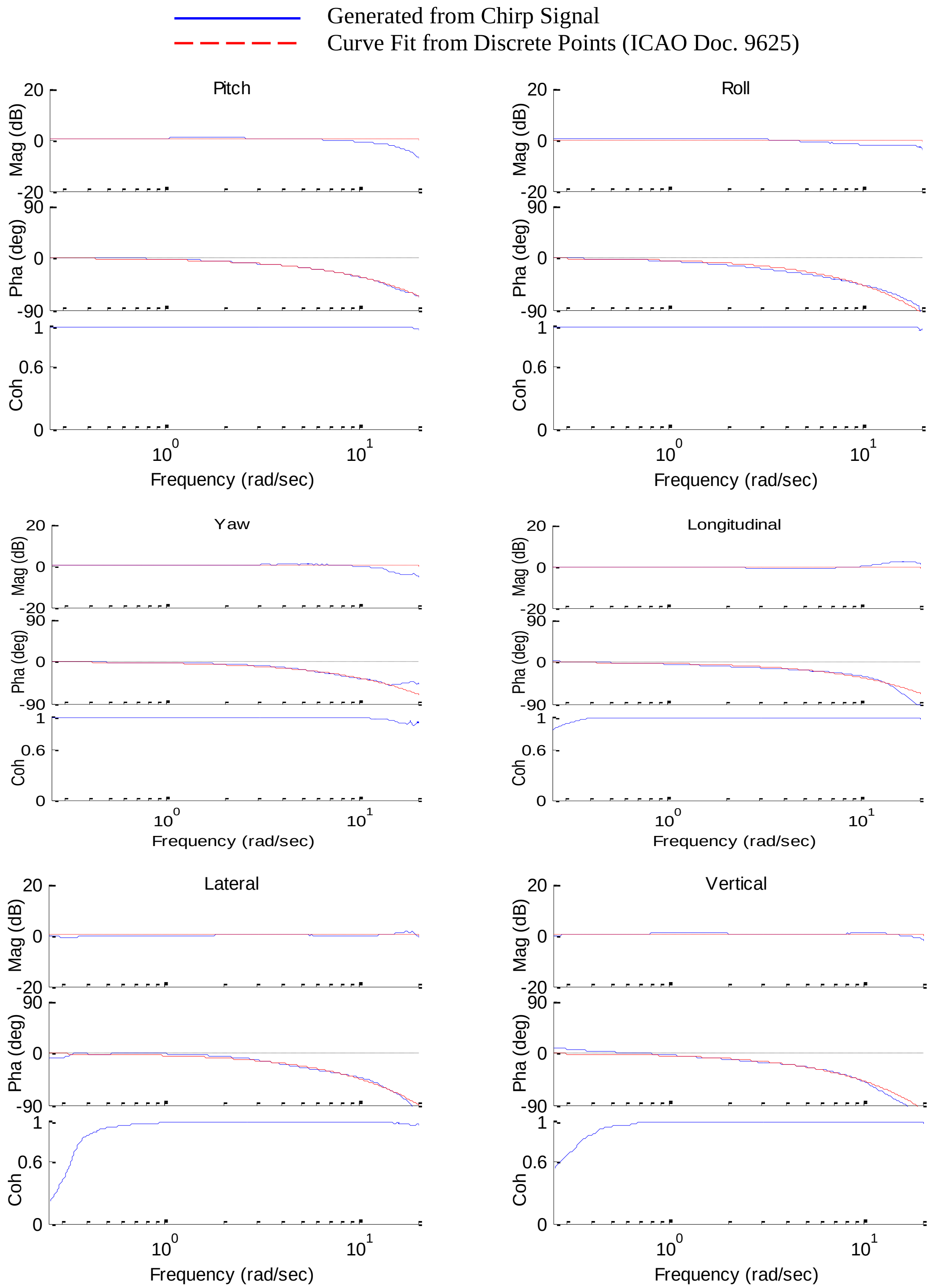
The need for the SFR scale is best illustrated by the results of the Slalom maneuver. The HQRs between flight and simulation were nearly identical yet the SFR ratings show that “Fidelity Warrants Improvement” based on task performance and technique adaptation. The SFR scale states that if “Fidelity Warrants Improvement” then there is limited transfer-of-training for the selected task but it is unclear if this is true for the Slalom manuever. The technique used in the simulator may have also worked in actual flight with equivalent performance.

Based on the results of the SFRE simulation the following are recommendations when recording SFR ratings after the first simulation run as recommended by the SFR scale developers:

- Maneuvers should be designed to give the pilot the opportunity to adapt their technique and obtain appropriate performance.
- Pilots should be given the opportunity to get acquainted with the simulator layout if different from the aircraft.
- Longer duration and repetitive tasks such as the Slalom maneuver are better than short duration tasks such as the Vertical maneuver for assessing simulator fidelity using the SFR scale.

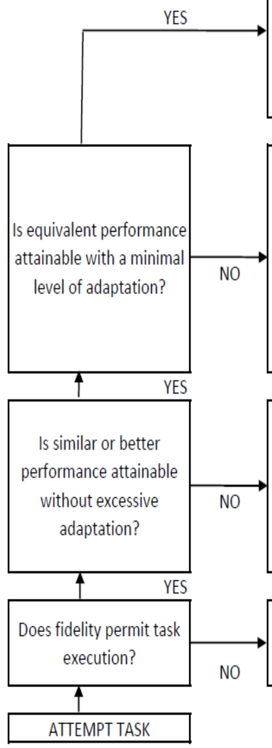
# Appendix A

VMS Motion System Performance



**Appendix B**

SFR Scale




| FIDELITY CHARACTERISTICS | COMPARATIVE TASK PERFORMANCE | AND/OR | PILOT'S TASK STRATEGY | FIDELITY RATING | FIDELITY LEVEL |
|---|---|---|---|---|---|
| **FIT FOR PURPOSE**<br>Full transfer of training for the selected task.<br>Simulator training sufficient for acquisition/maintenance of operational performance. | Equivalent performance attainable | *and* | Negligible or less adaptation of task strategy | 1 | 1 |
| | | *and* | Minimal adaptation of task strategy | 2 | |
| **FIDELITY WARRANTS IMPROVEMENT**<br>Limited transfer of training for the selected task.<br>Additional training required for operational performance. | Similar performance attainable | *and* | Minimal adaptation of task strategy | 3 | 2 |
| | Equivalent performance attainable | *and* | Moderate adaptation of task strategy | 4 | |
| | Similar performance attainable | *and* | Moderate adaptation of task strategy | 5 | |
| | Similar or equivalent performance attainable | *and* | Considerable adaptation of task strategy | 6 | |
| **NOT FIT FOR PURPOSE**<br>**IMPROVEMENT MANDATORY**<br>Negative transfer of training occurs. | Similar or equivalent performance attainable | *and* | Excessive adaptation of task strategy | 7 | 3 |
| | Similar performance not attainable | *and* | Considerable or less adaptation of task strategy | 8 | |
| | Similar performance not attainable | *and* | Excessive adaptation of task strategy | 9 | |
| **NOT FIT FOR PURPOSE**<br>**IMPROVEMENT MANDATORY**<br>Task cannot be performed. | Similar performance not attainable | *or* | An entirely inappropriate task strategy is required | 10 | 4 |

# Appendix C

SFRE Questionnaire

| Task Performance/ Aggressiveness (only rate the states featured in task definition) | | Far worse performance achieved in modified model (dissimilar) | Worse performance achieved in modified model (similar) | Achieved Performance Equivalent | Better performance achieved in modified model (similar) | Far better performance achieved in modified model (dissimilar) |
|---|---|---|---|---|---|---|
| Roll | N/A | | | | | |
| Pitch | N/A | | | | | |
| Yaw | N/A | | | | | |
| Lateral Pos. | N/A | | | | | |
| Longitudinal Pos. | N/A | | | | | |
| Heave/Vertical Pos. | N/A | | | | | |
| Speed | N/A | | | | | |
| Overall | N/A | | | | | |
| | Aggressiveness | | | | | |
| Comments highlight worst case and dominating phases | | | | | | |

| Task Strategy (Flight dynamics) | Modified model characteristics give represetative strategy | Minimal strategy adaptation required | Moderate startegy adaptation required | Considerable strategy adaptation required | Extensive adaptation required | Completely dissimilar strategy required |
|---|---|---|---|---|---|---|
| Lat. Cyclic | | | | | | |
| Long. Cyclic | | | | | | |
| Collective | | | | | | |
| Pedals | | | | | | |
| Comments highlight worst case | | | | | | |

| Task Strategy (Cueing Environment) | Cueing characteristics give representative startegy | Minimal strategy adaptation required | Moderate startegy adaptation required | Considerable strategy adaptation required | Extensive adaptation required | Completely dissimilar strategy required |
|---|---|---|---|---|---|---|
| Visual Cues | | | | | | |
| Motion Cues | | | | | | |
| Aural Cues | | | | | | |
| Inceptors | | | | | | |
| Vibration | | | | | | |
| Cockpit | | | | | | |
| Comments highlight worst case | | | | | | |

| HQR | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | | | | | | | | | | |
| Modified | | | | | | | | | | |
| Comments highlight main influencing factor(s) | | | | | | | | | | |

| SFR | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Comments highlight main influencing factor(s) | | | | | | | | | | |

**Appendix D**

Motion Gains and Washouts

| Axis | 1989 Experiments | | SimOpt 2012 | | | |
|---|---|---|---|---|---|---|
| | **All Tasks** | | **Bob Up** | | **Sidestep** | |
| | Gain | Washout(rad/s) | Gain | Washout(rad/s) | Gain | Washout(rad/s) |
| *Pitch* | 0.5 | 0.7 | 0.737 | 1.08 | 0.991 | 0.417 |
| *Roll* | 0.3 | 0.7 | 0.996 | 0.296 | 0.642 | 0.358 |
| *Yaw* | 0.5 | 0.5 | 0.993 | 0.1 | 1 | 0.1 |
| *Longitudinal* | 0.4 | 1.5 | 0.976 | 1.37 | 0.993 | 1.52 |
| *Lateral* | 0.8 | 0.6 | 0.927 | 0.332 | 0.74 | 0.264 |
| *Vertical* | 0.8 | 0.3 | 0.648 | 0.119 | 0.933 | 0.337 |

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